CNS/RIKEN Joint International Workshop
Physics of QCD Many Body Systems
--Future perspective based upon RHIC --
Nov.5-6, 2002

A dynamical approach to jet quenching in relativistic heavy ion collisions

Tetsufumi Hirano

Physics Department, University of Tokyo

Outline:

- Introduction & Motivation
- 3D Hydro Results
- The hydro+jet model
- Results@130A GeV
- Results@200A GeV
- Summary

Collaborator:

Yasushi Nara (Univ. of Arizona)

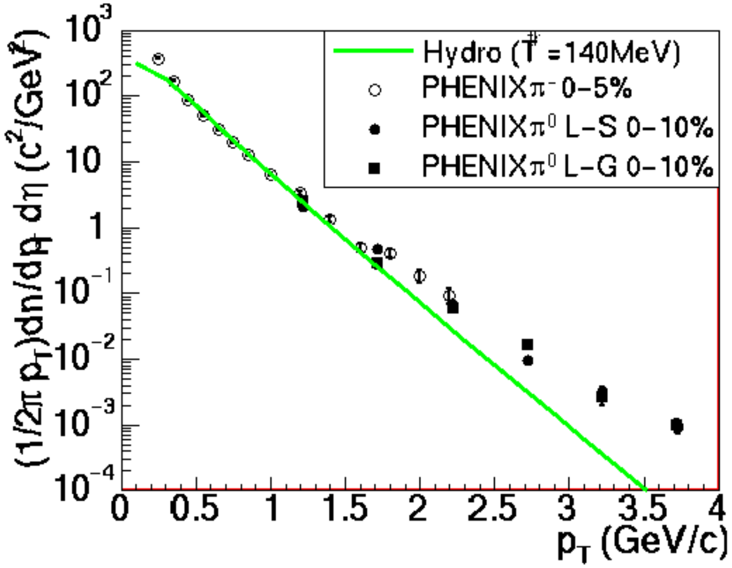
References:

T.Hirano and Y.Nara,
Phys. Rev. C **66**, 041901(R) (2002).

Introduction & Motivation

•A recent result from hydro with early chemical freeze-out
→p_T slope is insensitive to T^{th}.

T.Hirano and K.Tsuda, nucl-th/0205043 (PRC, in press).



Au+Au 130*A* GeV (central)

•Hard components can fill in the difference between the data and the hydro result.

The Hydro+Jet Model

(as a dynamical tool to analyze jet quenching)

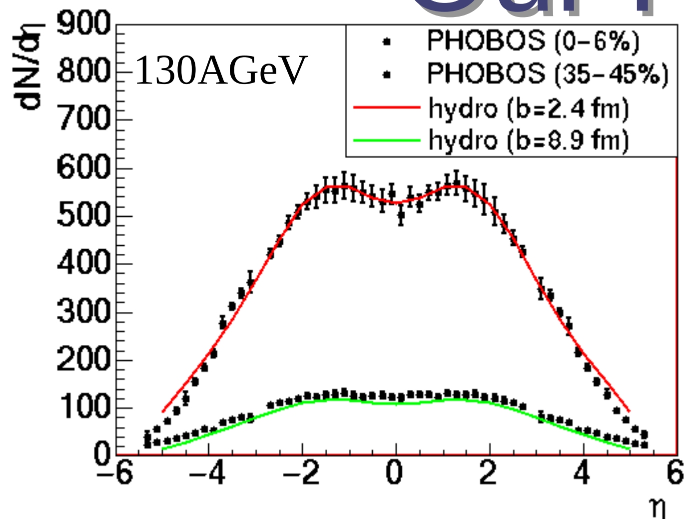
•Soft : Full 3D hydrodynamics (with early chemical f.o.)

•Hard: pQCD with parton energy loss

p_T spectra, $R_{AA}(p_T)$ and $C_2(\Delta\phi)$ in moderate high p_T (2-10 GeV/c) @RHIC

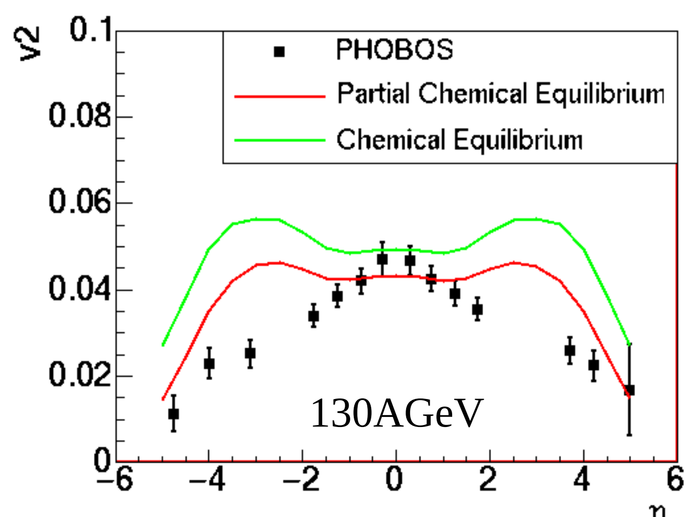
3D Hydro

Brief Summary of Our Hydro Results



- Full 3D hydro!
  - ✧ No Bjorken scaling ansatz
  - ✧ No cylindrical symmetry
  - ✧ (τ, η_s, x, y) coordinate

T.Hirano, Phys.Rev.C65(2002)011901.

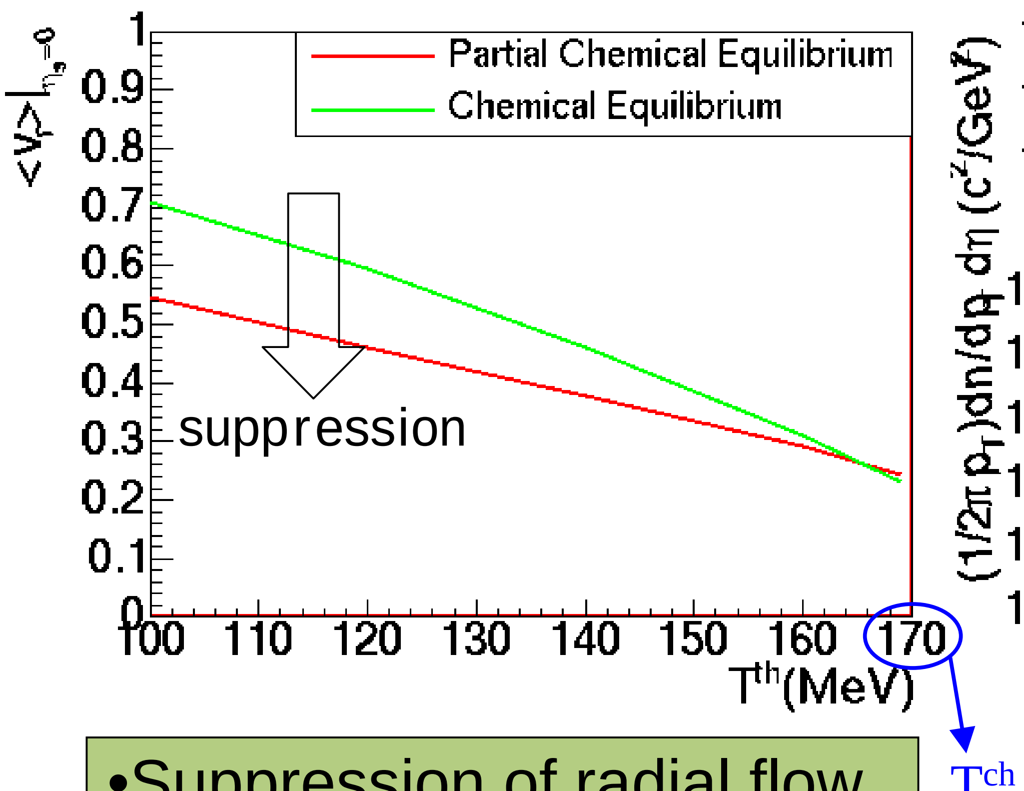


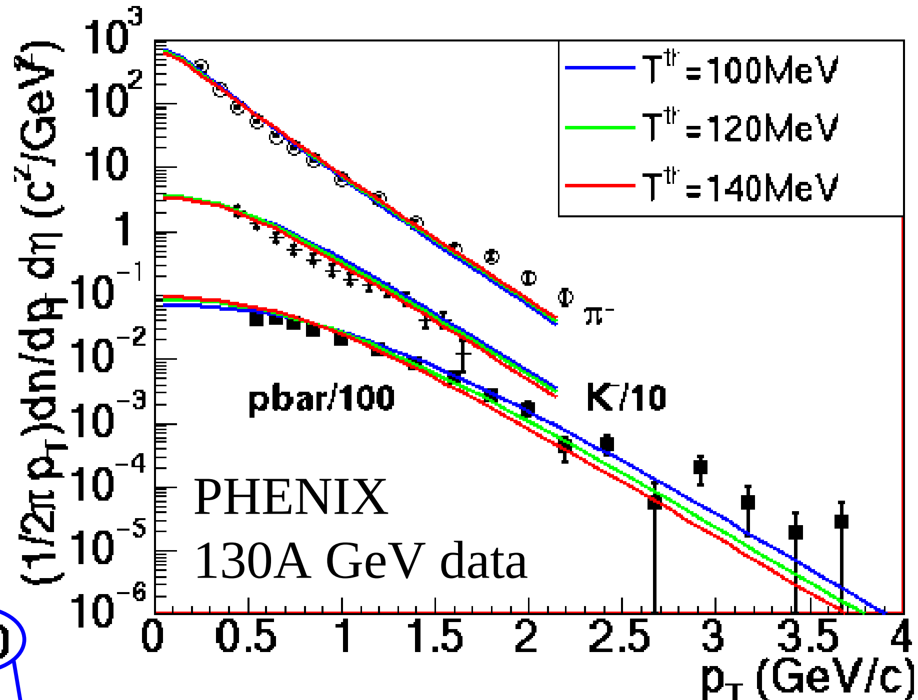
- $T^{\mathrm{ch}} \neq T^{\mathrm{th}}$!

➢Suppression of radial, elliptic flow and HBT radii in comparison with the conventional hydro results.

T.Hirano and K.Tsuda, nucl-th/0205043 (Phys.Rev.C, in press).

Brief Summary of Our Hydro Results (contd.)





- Suppression of radial flow as a result of chemical non-equilibrium properties

- p_T slopes become insensitive to T^{th}.
  → Need hard components

Why jets at RHIC and LHC?

Our definition of a jet:
A parton with p_T>2 GeV/c just after a collision
(often called "mini-jet")

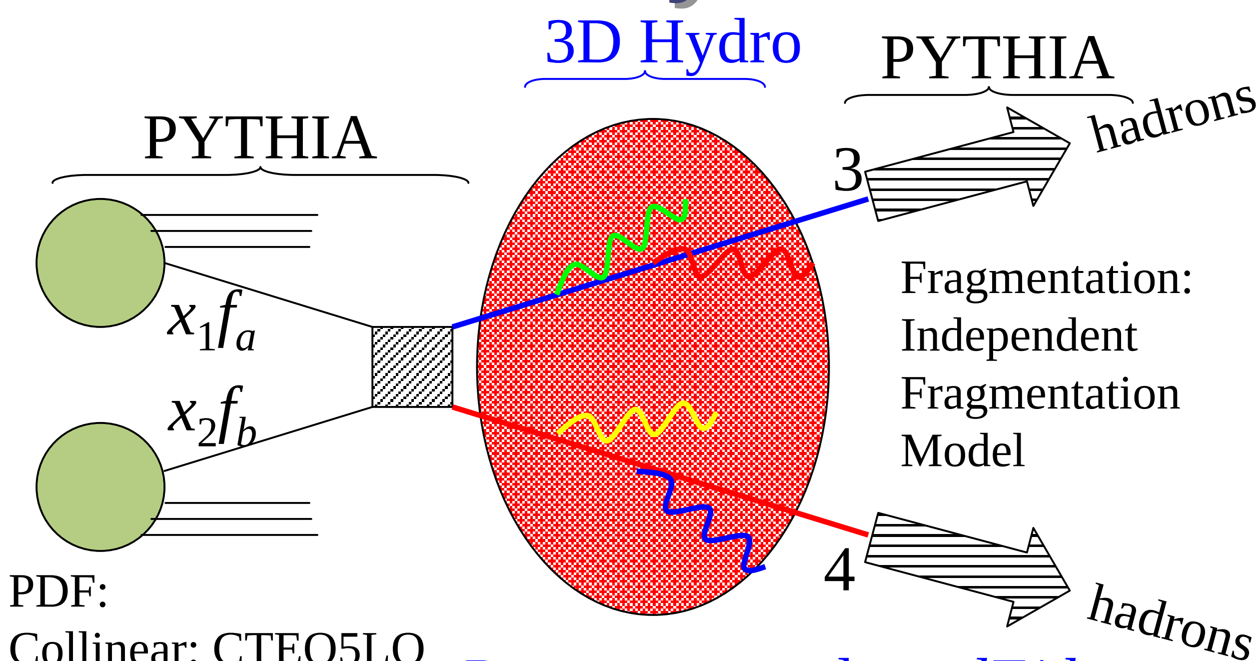
SPS	RHIC	LHC
Pb+Pb@20A GeV	Au+Au@200A GeV	Pb+Pb@5500A GeV
σ_{in} ~ 32 mb	σ_{in} ~ 40 mb	σ_{in} ~ 90 mb
σ_{jet} ~ 0.1 mb	σ_{jet} ~ 20 mb	σ_{jet} ~ 90 mb
N_{coll} = 923 (b=2 fm)	N_{coll} = 1067 (b=2 fm)	N_{coll} = 2600 (b=2 fm)
→ ~3 jets/event	→~500 jets/event	→~2600 jets/event

Copious jets at RHIC and LHC!
→ Need contribution from jets

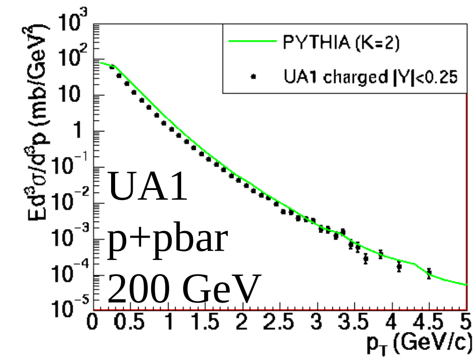
*pp:PYTHIA with CTEQ5L+K factor(K=2), AA:standard Woods-Saxon nuclear density

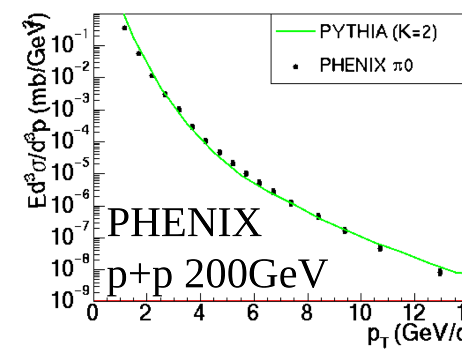
Hydro + Jet

The Hydro+Jet Model



Fragmentation:
Independent
Fragmentation
Model





PDF:
Collinear: CTEQ5LO
k_T: Gaussian
$\langle k_T^2 \rangle = 1\,\mathrm{GeV}^2/c^2$

Parton energy loss: dE/dx
(I will discuss later…)

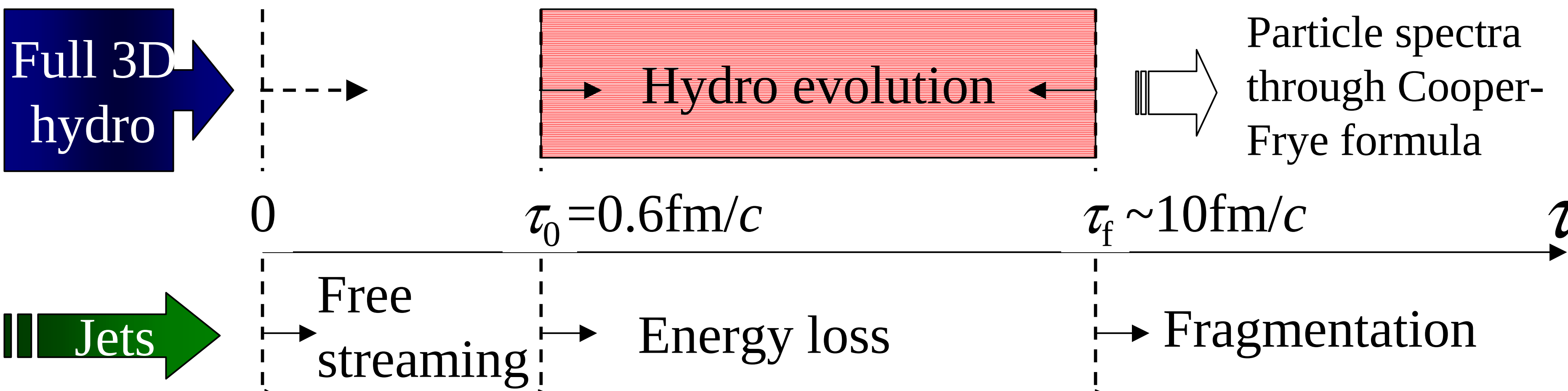
$$E\frac{d\sigma^{pp}_{\text{jet}}}{d^3p} = K\sum_{ab}\int g(k_{T,a})k_{T,a}dk_{T,a}\, g(k_{T,b})k_{T,b}dk_{T,b}$$
$$\times \int f_a(x_1,Q^2)dx_1\, f_b(x_2,Q^2)dx_2\, E\frac{d\sigma^{ab\to cd}}{d^3p}$$

pQCD LO:

$$q+q' \to q+q',\ q+\bar{q} \to q'+\bar{q}'$$
$$q+\bar{q} \to g+g,\ q+g \to q+g$$
$$g+g \to q+\bar{q},\ g+g \to g+g$$

*Initial and final state radiation are included.

Time Evolution in the Hydro+Jet Model



•Formation time~0 fm
For jets with p_T>2GeV/c,
1/p_T<0.1fm/c<<1fm/c

•Momentum dist. from PYTHIA ver. 6.2

•Thermalization time = Initial time of fluids

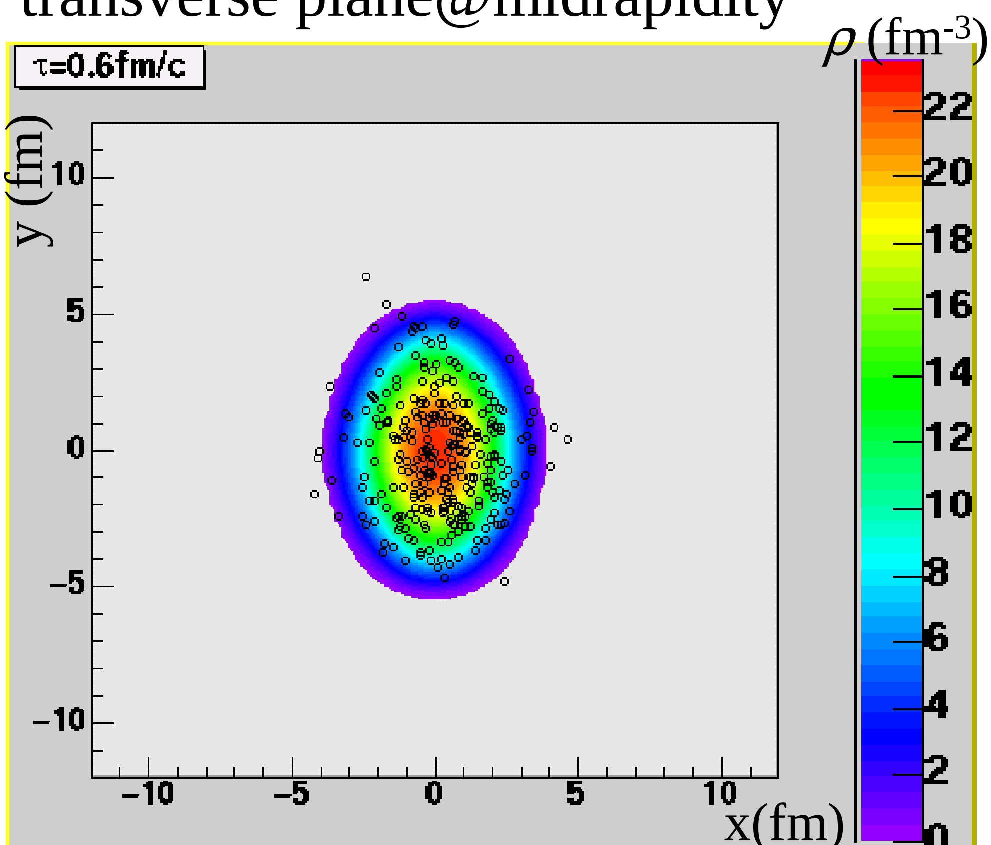
•Initial parameters in hydro have been already tuned.

•After hydro simulation, all survival jets fragment into hadrons.

•We neglect interaction of fragmented hadrons.

Jets and Hydro Evolution in the Transverse Plane

Au+Au 200*A*GeV, *b*=8 fm
transverse plane@midrapidity



Gradation
→ *Themalized* parton density
Plot (open circles)
→ Jets (p_T>2GeV/c)

- Initial configuration of jets
→Prop. to # of binary collisions
- Assuming jets move along straight paths (eikonal approximation)

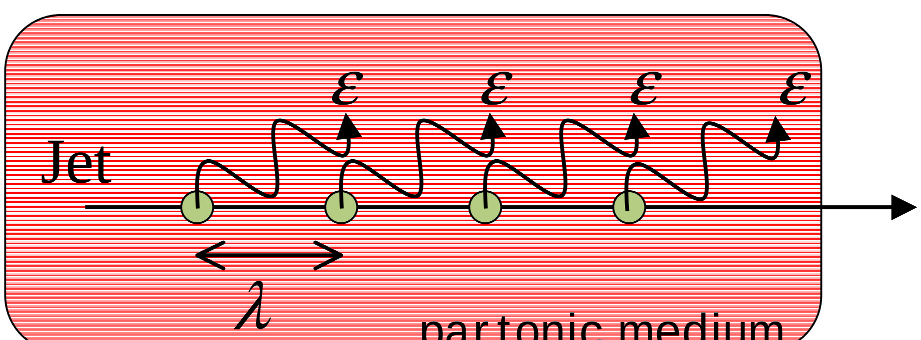
Phenomenological Parton Energy Loss

- **Incoherent Model:**

$$\frac{dE}{dx} = \frac{\varepsilon}{\lambda} = \varepsilon\sigma\rho(\tau, \mathbf{x}(\tau))$$

From hydro simulation

ε: energy deposit per scattering
λ: mean free path
σ: parton-parton cross section
ρ: thermalized parton density



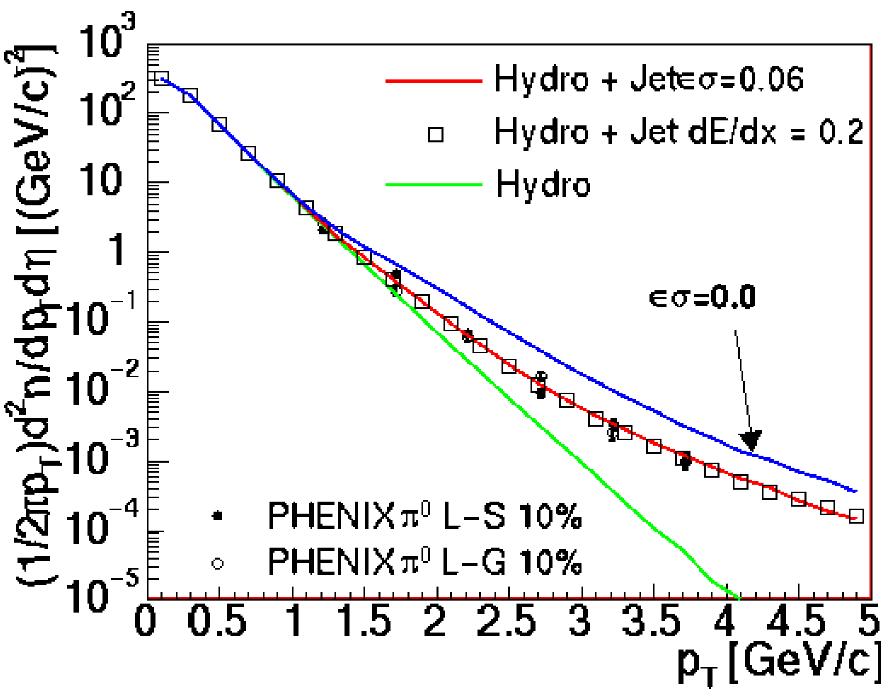
*Neglecting energy loss in the hadron phase.

$$\rho_{\mathrm{mixed}} = f_{\mathrm{QGP}}(\tau, \mathbf{r})\rho(T_{\mathrm{C}})$$

$$f_{\mathrm{QGP}} = \frac{E(\tau, \mathbf{r}) - E_{\mathrm{had}}}{E_{\mathrm{QGP}} - E_{\mathrm{had}}}$$

Results @130AGeV & 200AGeV

π^0 Spectra in $s_{NN}^{1/2}$=130 GeV Central Collisions



- <dE/dx>~0.85 GeV/fm @τ_0=0.6 fm/c
- Onset of hard component p_T~1.5 GeV/c

$$\frac{dE}{dx} = \underline{0.06}\,\rho(\tau, \boldsymbol{r})\ (\text{GeV/fm})$$

the best fit value

$$\approx 0.2\,(\text{GeV/fm})$$

HIJING:
dE/dx = 0.25 (GeV/fm)

X.-N. Wang, NPA698(2002)296c

Models for Parton Energy Loss

- **Incoherent model**

$$\frac{dE}{dx} = 0.06\rho(\tau, \mathbf{x}(\tau))$$

- **Coherent (LPM) model**

A model motivated by

a) GLV 1st order, or b) BDMPS for $E > E_{cr}$

$$\Delta E = a\hat{q}L_{\mathrm{eff}}^{2},$$ *a*: free (adjustable) parameter

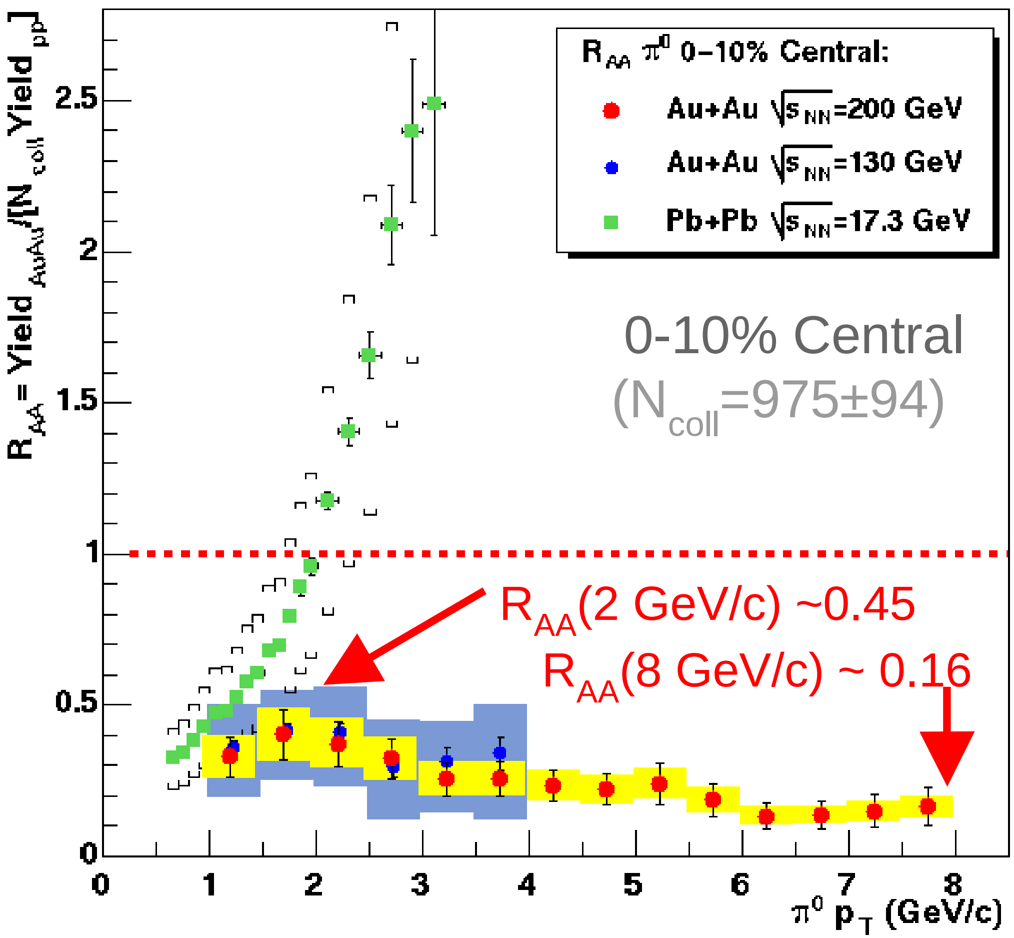
“Transport” coefficient *q*

$$\hat{q}L_{\mathrm{eff}}^{2} = \int_{\tau_0}^{\tau_f} d\tau\rho(\tau, \mathbf{x}(\tau))(\tau - \tau_0)\log\left(1 + \frac{2E}{L\mu^2}\right)$$

$L \sim R_{\mathrm{Au}}$
$\mu = 0.5$ GeV/c

M.Gyulassy *et al.*, Nucl.Phys.**B571**(2000)197; R.Baier *et al.*, Nucl.Phys.**B483**(1997)291.

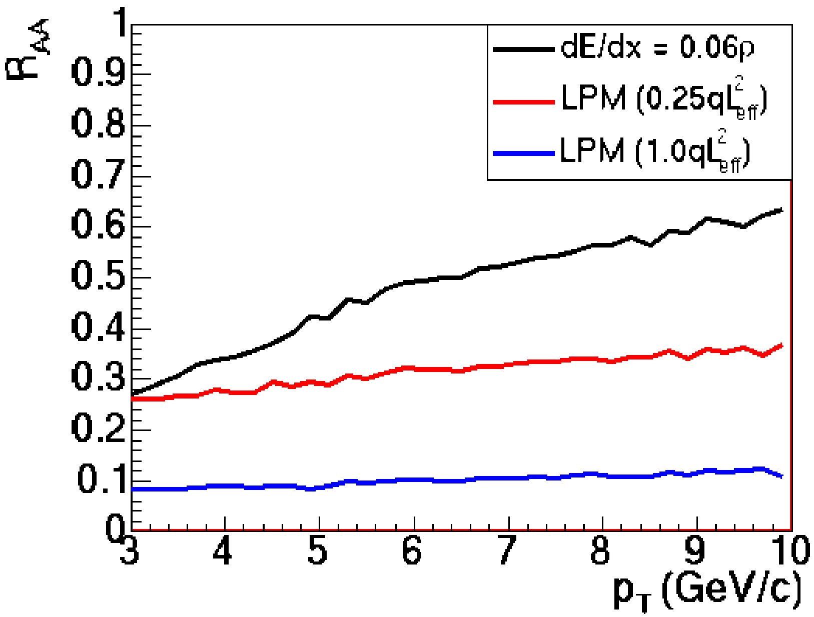
Suppression Factor (PHENIX)



$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{N+N}/dp_T d\eta}$$

From D. d'Enterria, talk at QM2002.

Suppression Factor in $s_{NN}^{1/2}$=200 GeV Central Collisions



- Suppression factor R_{AA}
  Incoherent model: increase
  Coherent model: almost flat

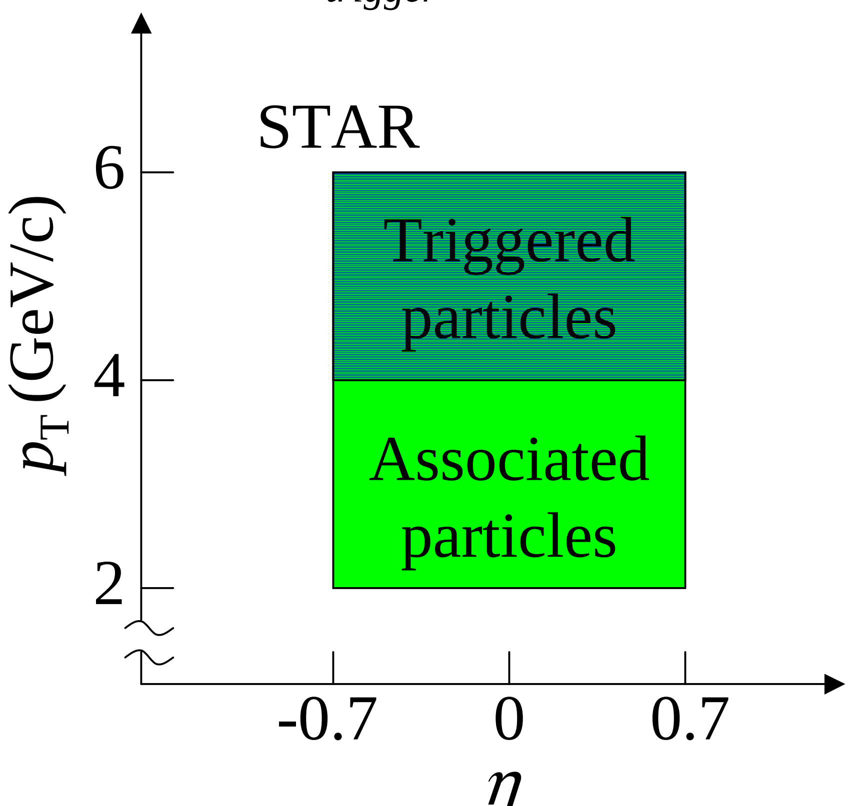
- Experimental data (PHENIX):
  → gradually decrease

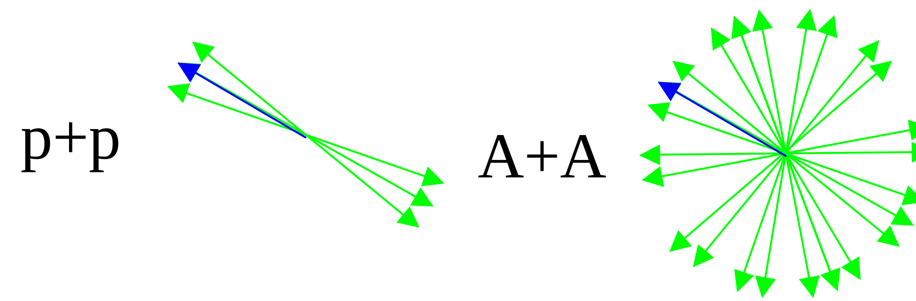
$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{N+N}/dp_T d\eta}$$

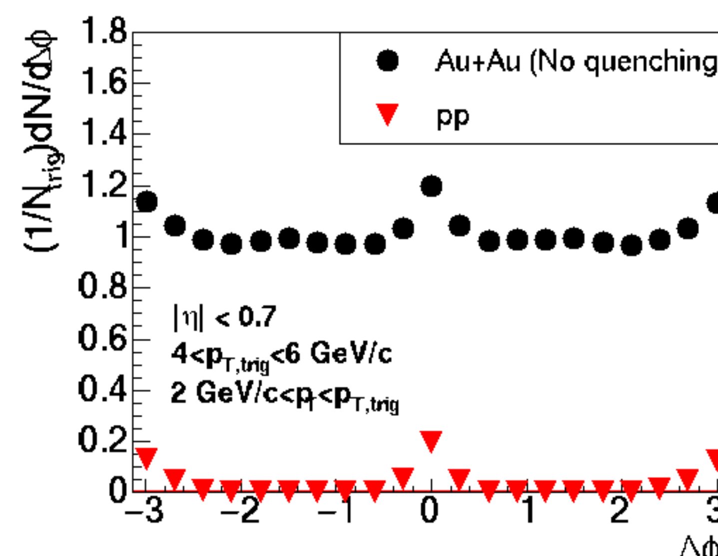
$R_{AA}(p_T)$ depends on the models of parton energy loss.

Back-to-Back Correlations of High p_T Hadrons

$$C_2(\Delta\phi) = \frac{1}{N_{trigger}} \int d\Delta\eta \frac{dN}{d\Delta\phi\, d\Delta\eta}$$

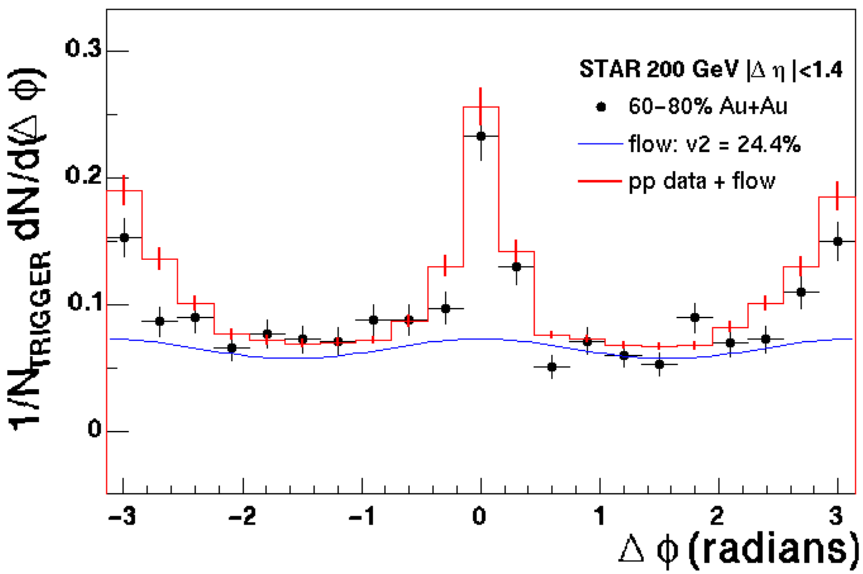




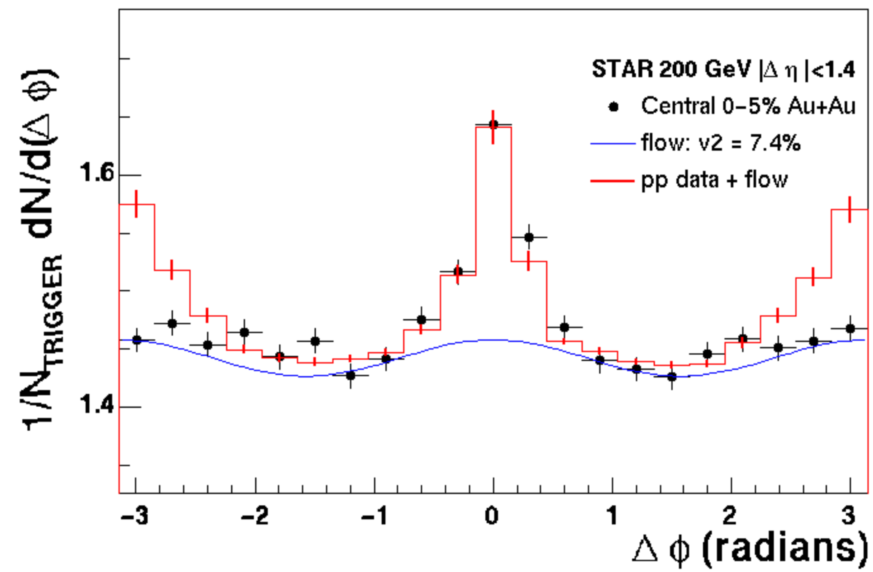


Back-to-Back Correlation (STAR)

4<pt(trig)<6 GeV/c data



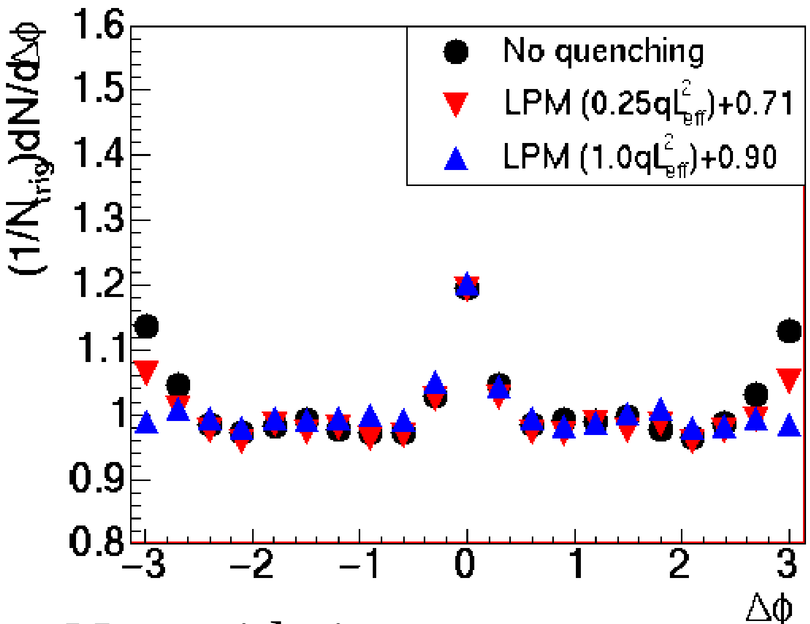
Peripheral 60-80%

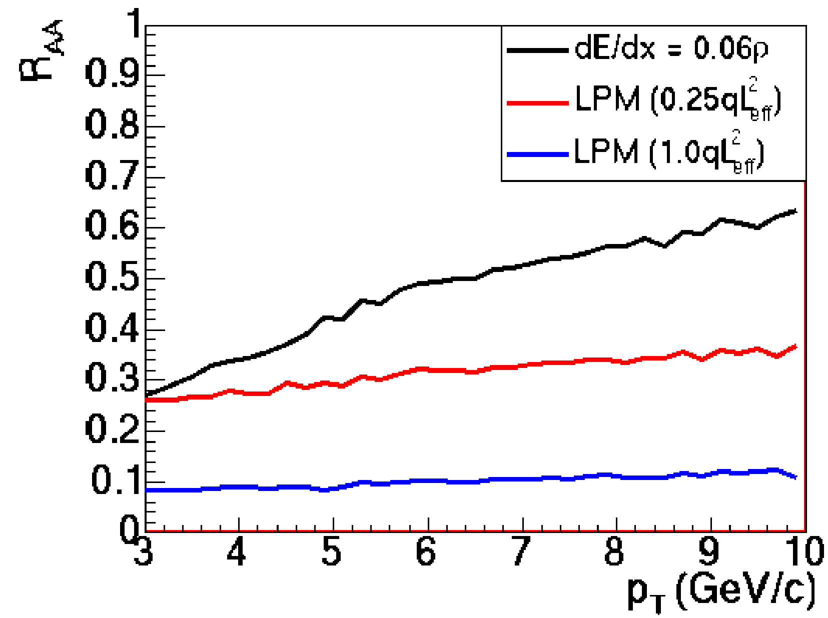


Central 0-5%

From D.Hardtke, talk at QM2002.

R_{AA} and C_2 in $s_{NN}{}^{1/2}$=200 GeV Central Collisions





- Near-side jets:

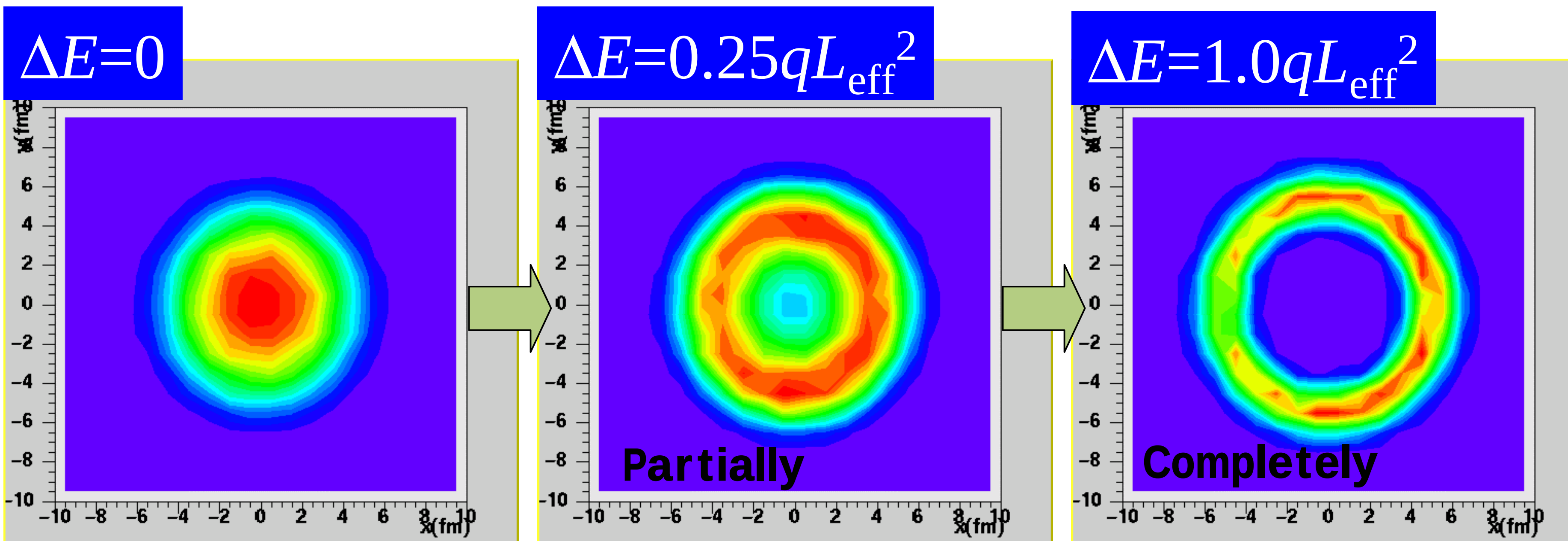
  Almost independent
- Away-side jets:

  Depend on magnitude of energy loss

We fail simultaneous reproduction of R_{AA} and C_2.
→Need another mechanism

Surface Emission Dominance ?

Initial positions of jets which survive at final time



An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with <u>one jet escaping without absorption and the other fully absorbed</u>. --J.D.Bjorken, FERMILAB-Pub-82/59-THY (1982).

Summary

- We construct the Hydro+Jet model as a dynamical approach to the physics of jet quenching.
  - **Au+Au 130AGeV**
  - The onset of hard contribution
    → p_T~1.5 GeV/c for pions
  - <dE/dx>=0.2 GeV/fm
    (⟺ HIJING:0.25 GeV/fm)
  - <dE/dx>~0.85 GeV/fm @τ_0=0.6 fm/c for incoherent model

Summary (contd.)

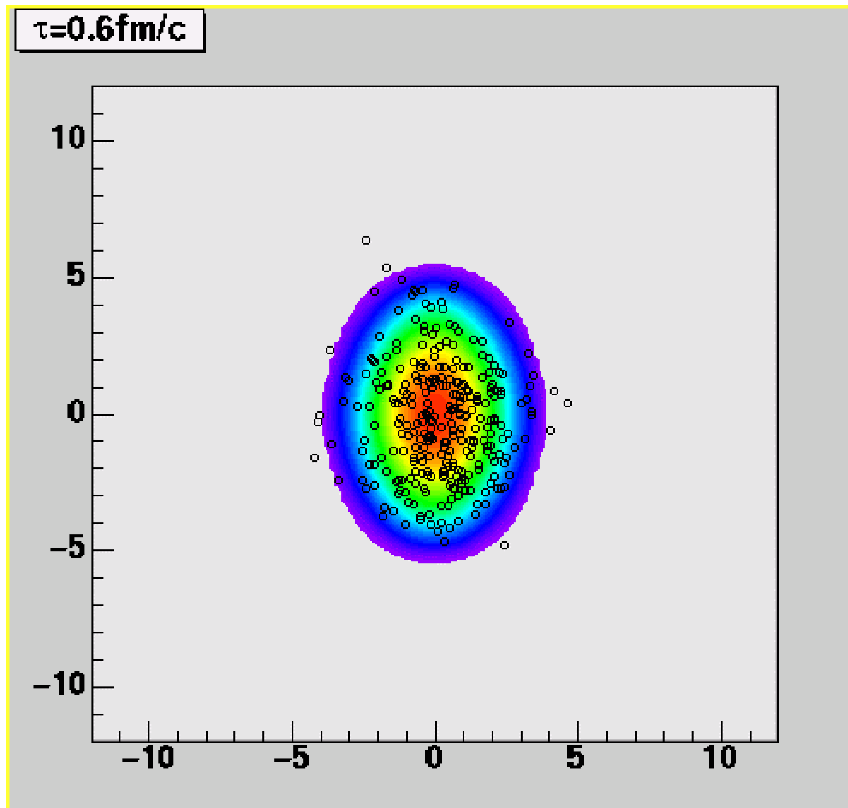
■**Au+Au 200AGeV**

➢$R_{AA}(p_T)$ is sensitive to the model dE/dx.

➢No parameter which reproduces $R_{AA}(p_T)$ and the disappearance of b-to-b correlation simultaneously.
→ Need other mechanisms (deflection of jets?)

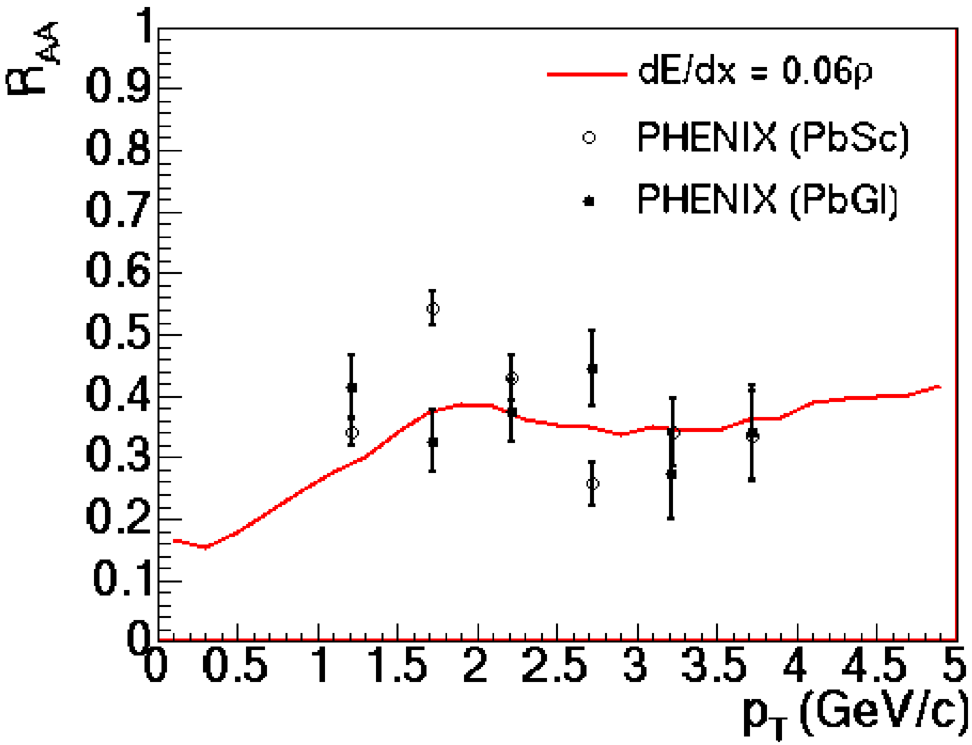
➢ (Partial?) surface emission of jets may happen in central collisions.

Thank you very much for your kind attention



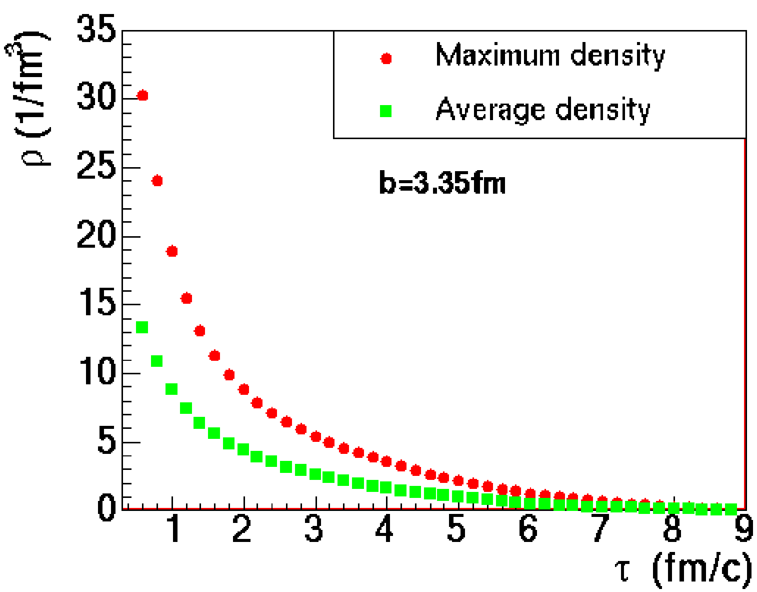
Spare Slides

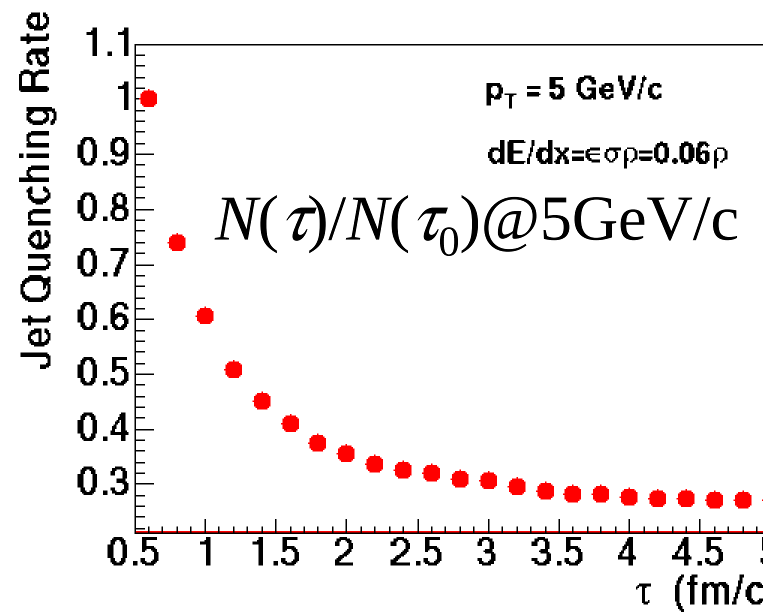
Suppression Factor in $s_{NN}^{1/2}$=130 GeV Central Collisions

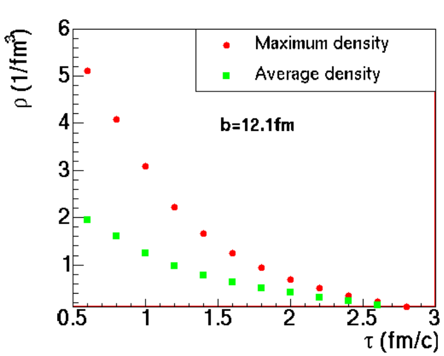


$$R_{AA}(p_T) = \frac{d^2 N^{A+A} / dp_T d\eta}{\langle N_{binary} \rangle d^2 N^{N+N} / dp_T d\eta}$$

Jet Quenching Rate in 130A GeV Collisions







- ρ prop. to $\sim 1/\tau$
- One should check LPM case

$$\Delta E \propto \int \rho(\tau)\tau d\tau$$

Comparison with Results by E.Wang and X.N.Wang

Our result (b=3.35 fm)

dE/dx=0.06ρ GeV/fm

- $<\rho(\tau=0.6$ fm/c$)>\sim14$ fm^{-3} $\rightarrow\sim0.85$ GeV/fm
- $\rho(\tau=0.6$ fm/c$)|_{max}\sim30$ fm^{-3} $\rightarrow\sim1.7$ GeV/fm

Wang and Wang (R=6 fm)

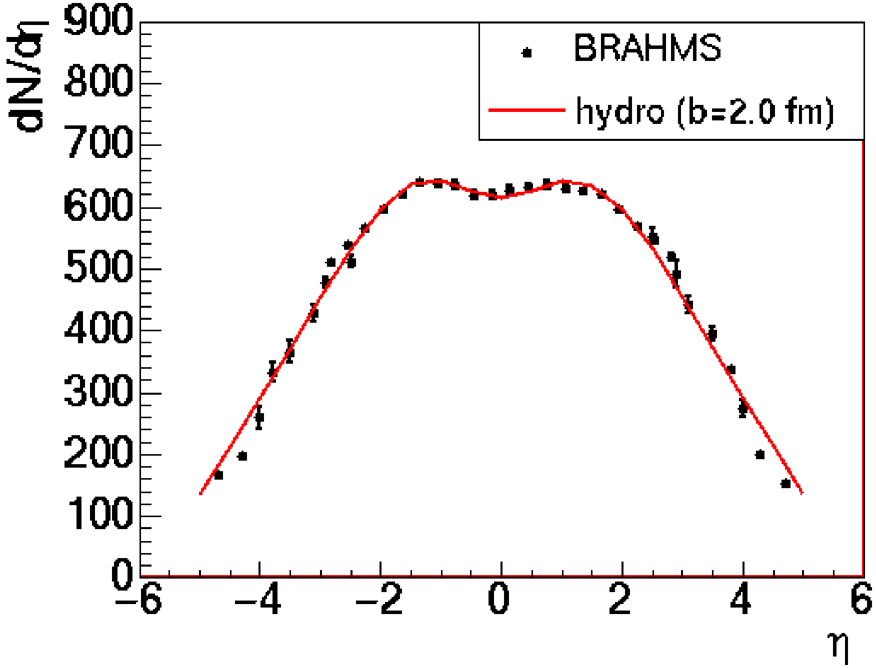
$dE/dx\sim0.34(2R/\tau_0)\ln E/\ln5$

- For 10 GeV parton,
  $dE/dx\sim7.3$ GeV/fm@τ_0=0.2fm/c
- For 4 GeV parton,
  $dE/dx\sim2.1$ GeV/fm@τ_0=0.6fm/c

The differnece comes from initial time, density profile energy dependence, and impact parameter.

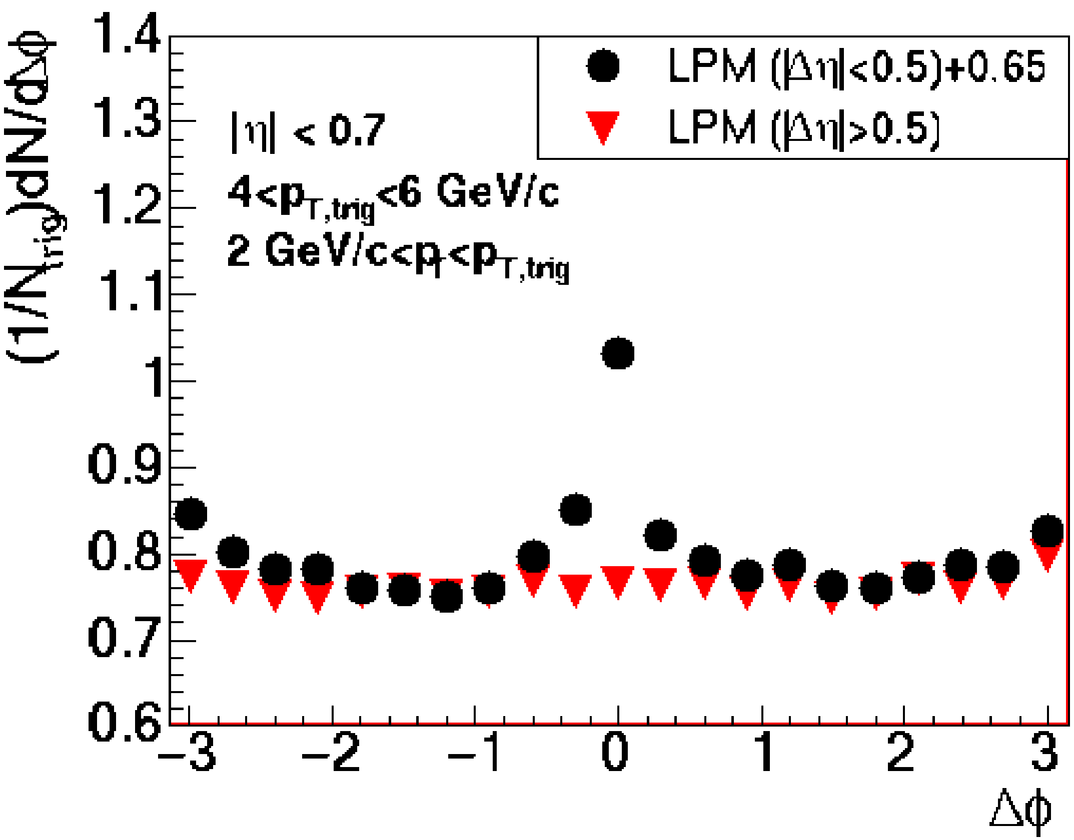
Our result is consistent with Wang and Wang result.

Hydro@200GeV



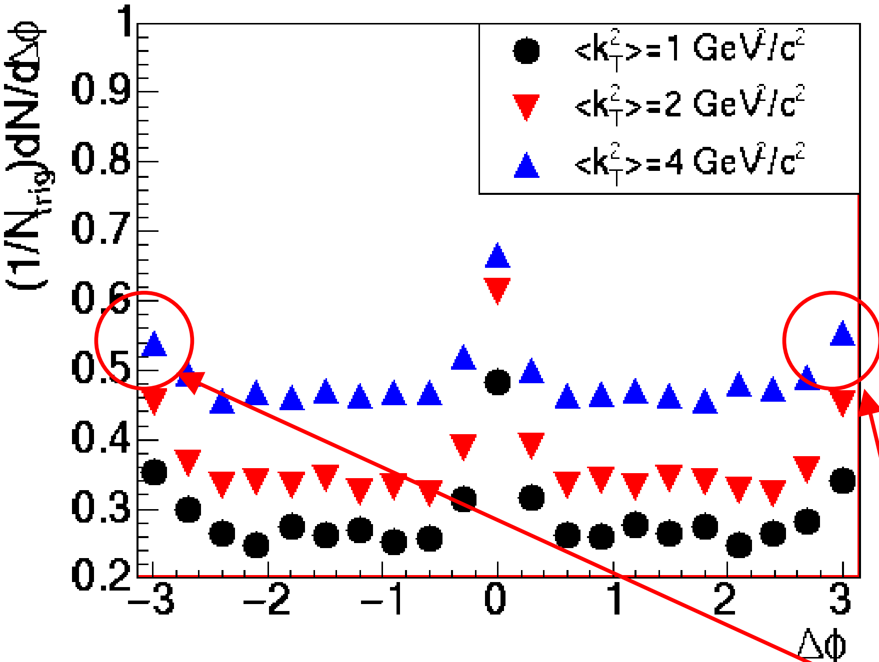
- E_0=40000MeV/fm^3
- Flat region η_{flat}=4.0
- Width η_{Gauss}=0.8
- Binary collision scaling in transverse plane

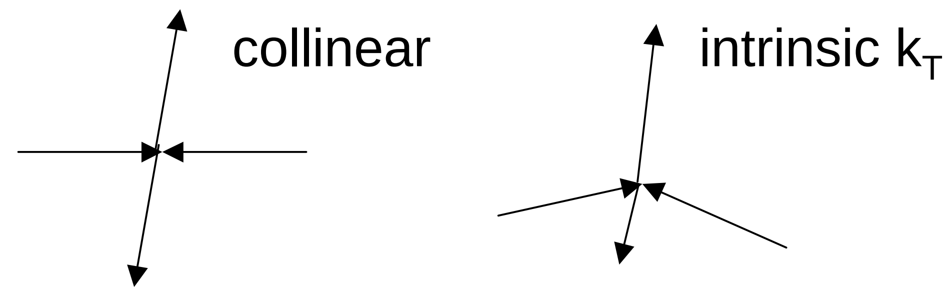
Relative Pseudorapidity Dependence of Jets



- $|\Delta\eta|<0.5$
  Clear peak at $\Delta\phi=0$
- $0.5<|\Delta\eta|<1.4$
  No peak at $\Delta\phi=0$

Intrinsic k_T of Partons in Nuclei?





Gaussian primordial k_T distribution of partons

$$g(k_T) \propto \exp(-k_T^2 / \sigma_T^2)$$

$$\langle k_T^2 \rangle = \sigma_T^2 = 1, 2 \text{ or } 4\,\mathrm{GeV}^2 / c^2$$

- Back-to-back correlation of jets
  - Energy loss ($0.25qL_{eff}^2$)
  - + intrinsic k_T
  - Triggered: $4<p_T<6$ GeV/c,
  - Associated: $2<p_T<p_{T,trig}$

Intrinsic k_T is not the origin of disappearance of back-to-back correlation!

Discussions

- Many observables to be analyzed
  - v_2 in high p_T region
  - p_T spectra for (anti-)protons
  - $R_{AA}(p_T)$ in non-central collisions
    (R_{AA} really scales with N_{part} ?)
  - Jet quenching in off midrapidity region

  and so on…

- Many effects to be included
  - Deflection of jets in medium
  - Interaction between fragmented hadrons and thermalized hadrons

  (→hydro+jet+hadronic cascade model ?)